ITER Design Review

Physics Issues

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by

R. J. Hawryluk

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and
EU, JA, IO and USBPO contributors

STAC Review Identified Scientific Issues Requiring Near-Term Results

- **Update to the APS Town meeting.**

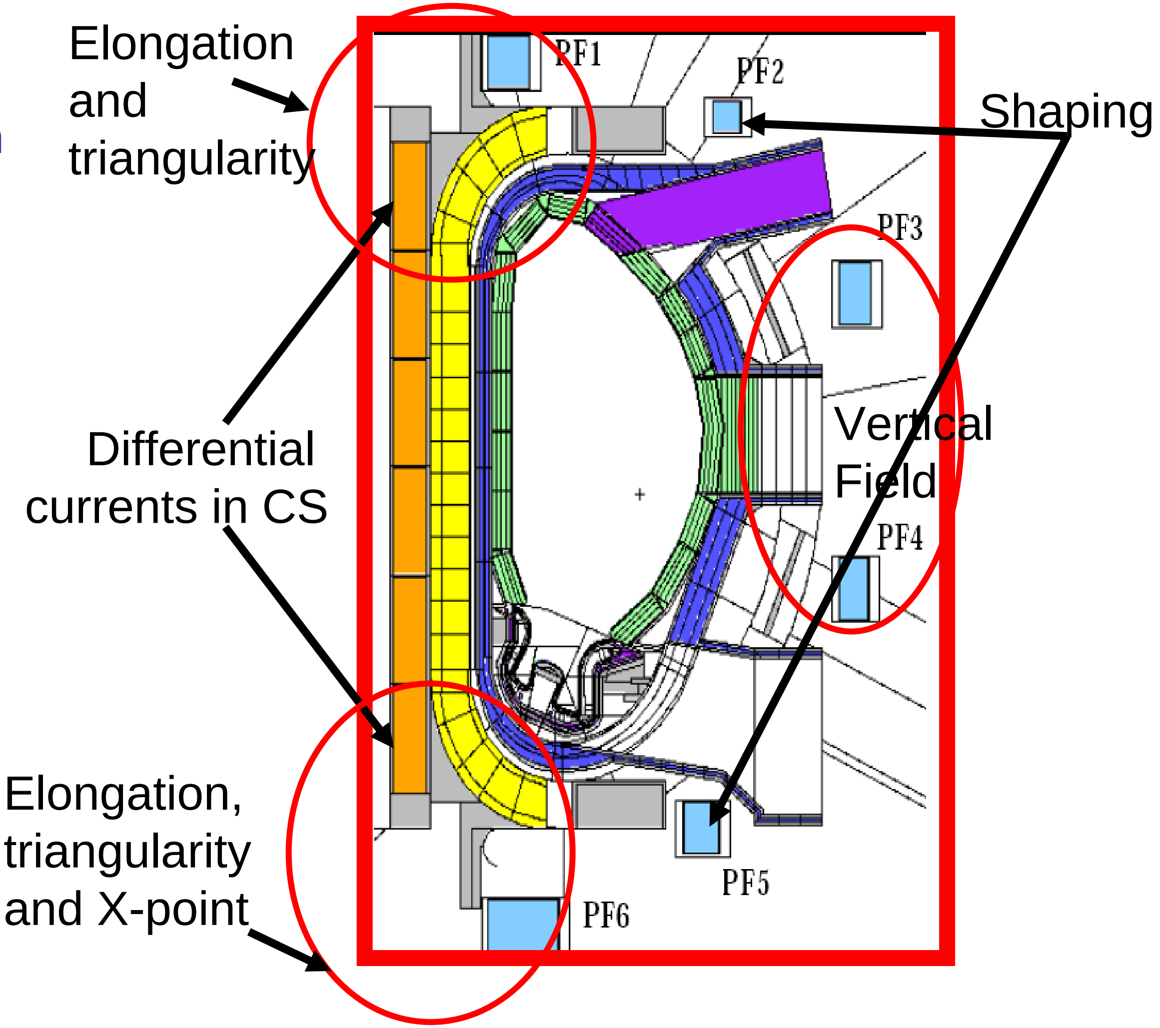
- **Focus of the talk is on physics issues STAC identified:**
  - **Plasma shaping**
  - **Volt-sec consumption**
  - **Vertical stability**
  - **ELM control**

- **This is not a comprehensive discussion of all of the physics issues.**
  - **USBPO has made many other important contributions not covered in this talk.**

ITER PF System Has Important Ramifications for Operations

- **TSC simulations performed of the plasma evolution show saturation of the PF currents, consequent loss of shape control and contact of the plasma with first wall PFCs for periods of seconds.**

- **Most usually, PF6 is the coil that saturates and, with it, PF2 and PF5. Some simulations show saturation of PF4. Also, vertical separation force in the solenoid is a limiting constraint. The field strength in the CS is another limit.**

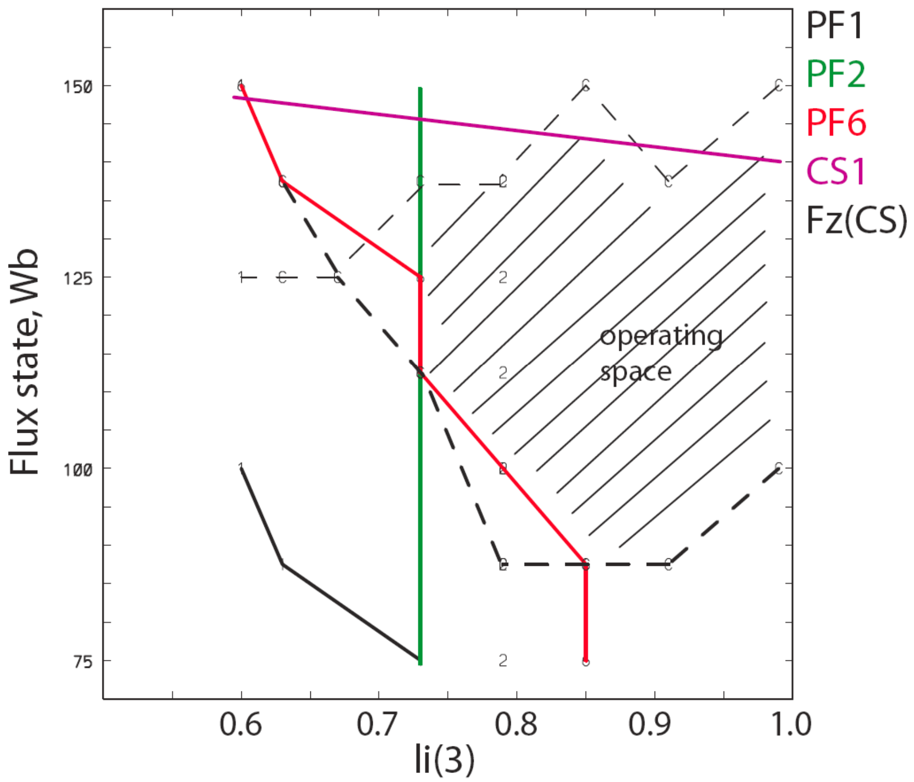


PF Coil Design Places Major Constraints on Operating Range Even During Burn Phase

Recent DIII-D li(3) results in low collisionality discharges:
- Elmy H-mode: .62-0.8
- Hybrid mode: 0.6
- Steady-state: .57
- Advanced Inductive: 0.62-0.8

T. Luce

using coil and CS force limits from 2/1/08

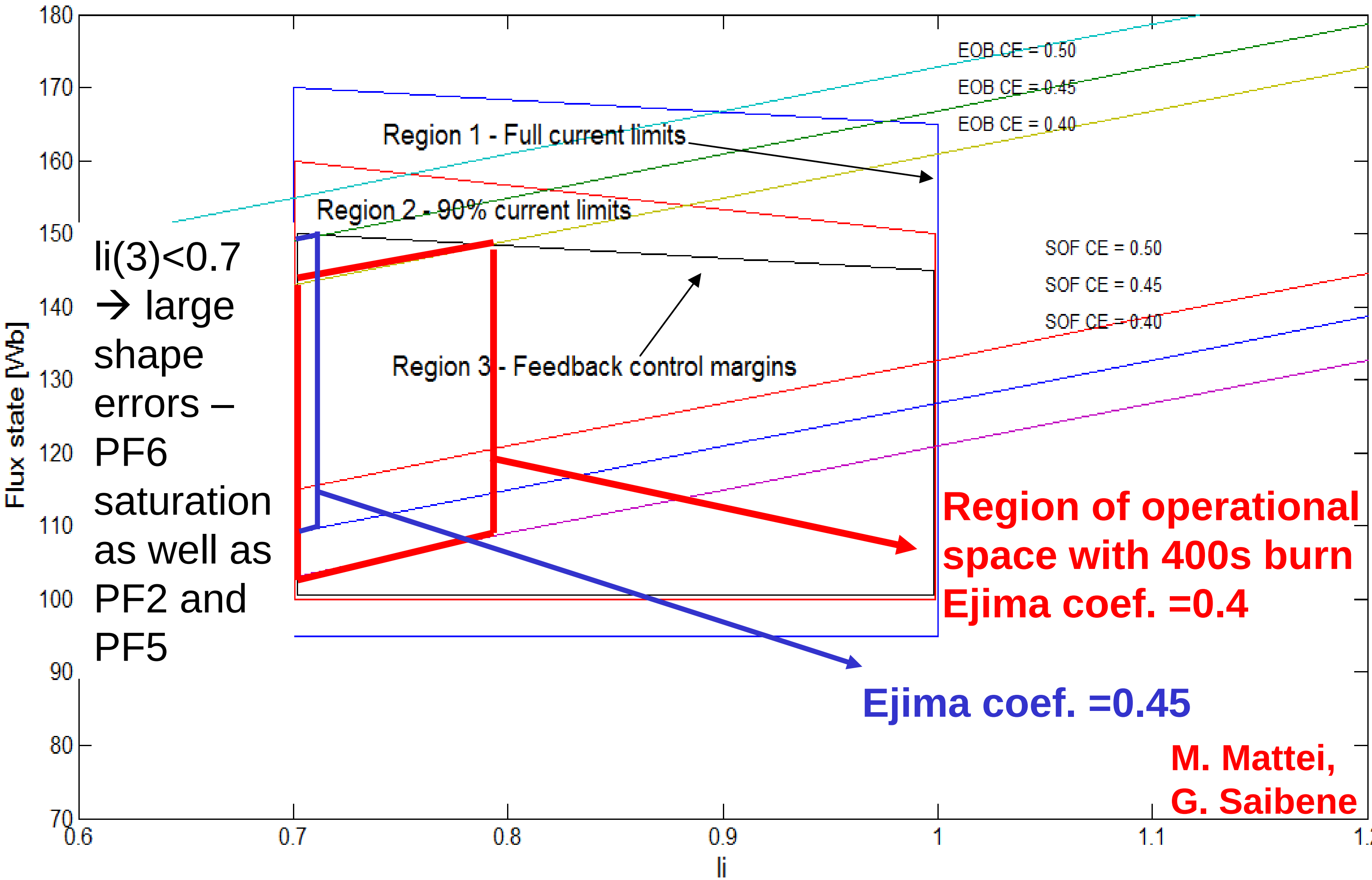


C. Kessel

Impact of feedback requirements not included.
Low internal inductance consequence of high pedestal temperature and bootstrap current.

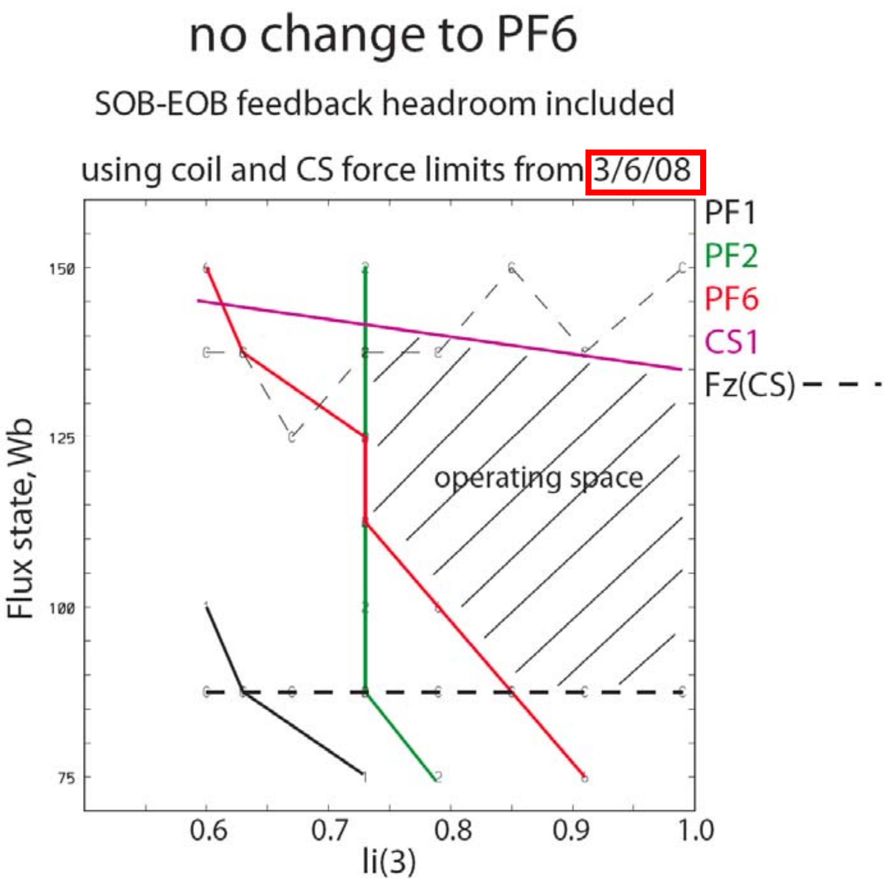
- High edge temperature required for high Q_{DT}.

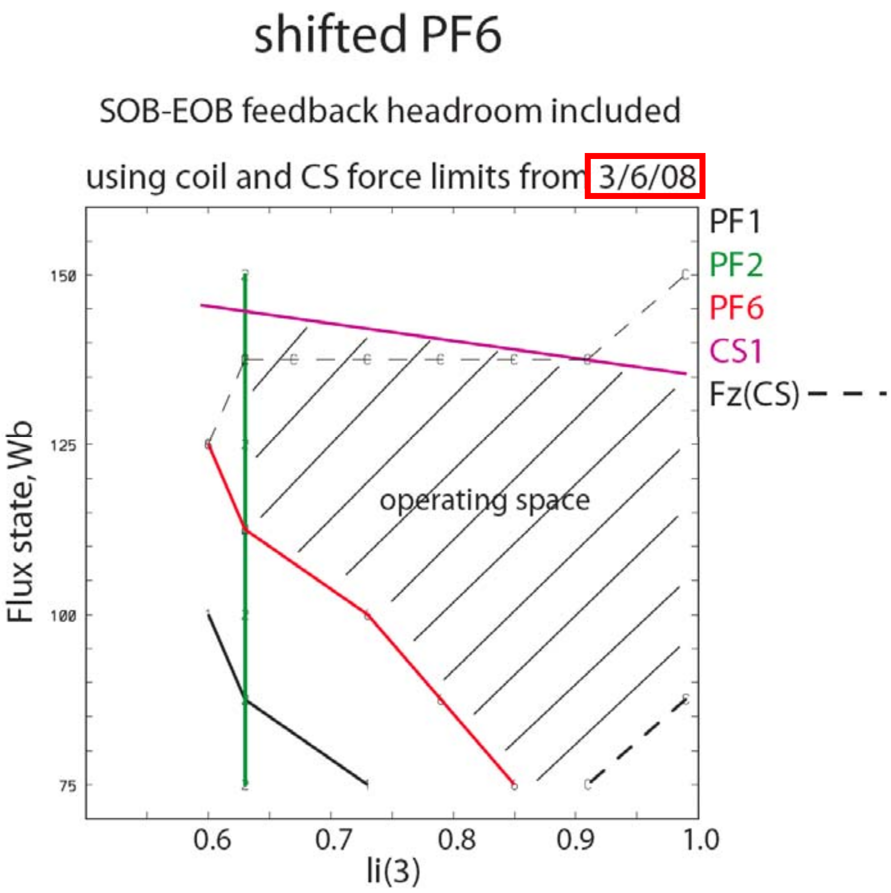
EU Performed Independent Analysis Taking Into Account V-sec, Feedback Control Margins but Relaxed Shape Constraints



Motivated re-examining machine limits again and changes to PF design.

Assessing Impact of Possible Changes to PF Design



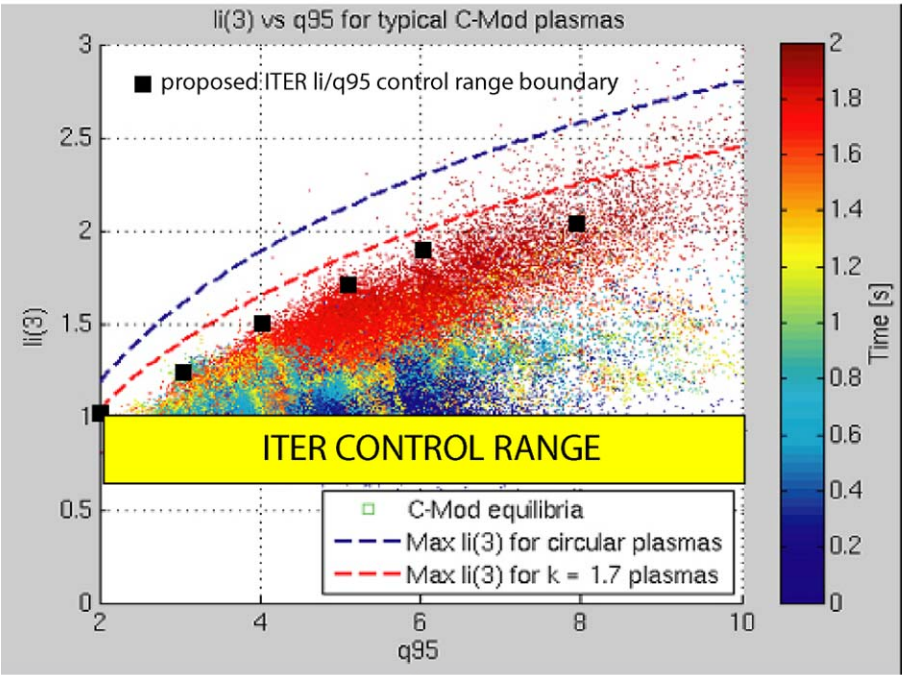


C. Kessel

- **The new limits increased the operating space.**
- **Can we refine the requirements for feedback headroom & control of strikepoint control?**
- **Should we modify PF2 and perhaps PF5? More to be done!**

Vertical Position Control Must be Robust & Reliable in ITER

- **Loss of vertical plasma position control in ITER will cause thermal loads on PFC of 30-60 MJ/m^2 for ~0.1s.**
  - **PFCs cannot be designed to sustain (repetitive) thermal loads like those quoted above.**
- **VDE also generates the highest electromagnetic loads**
  - **A phenomenological extrapolation of horizontal forces from worst JET cases implies horizontal loads ~45MN on ITER vacuum vessel.**
  - **MHD wetted kink model developed to simulate the horizontal loads predicts ~20MN. (Zakharov)**
  - **Vertical loads ~90MN (Humphreys)**



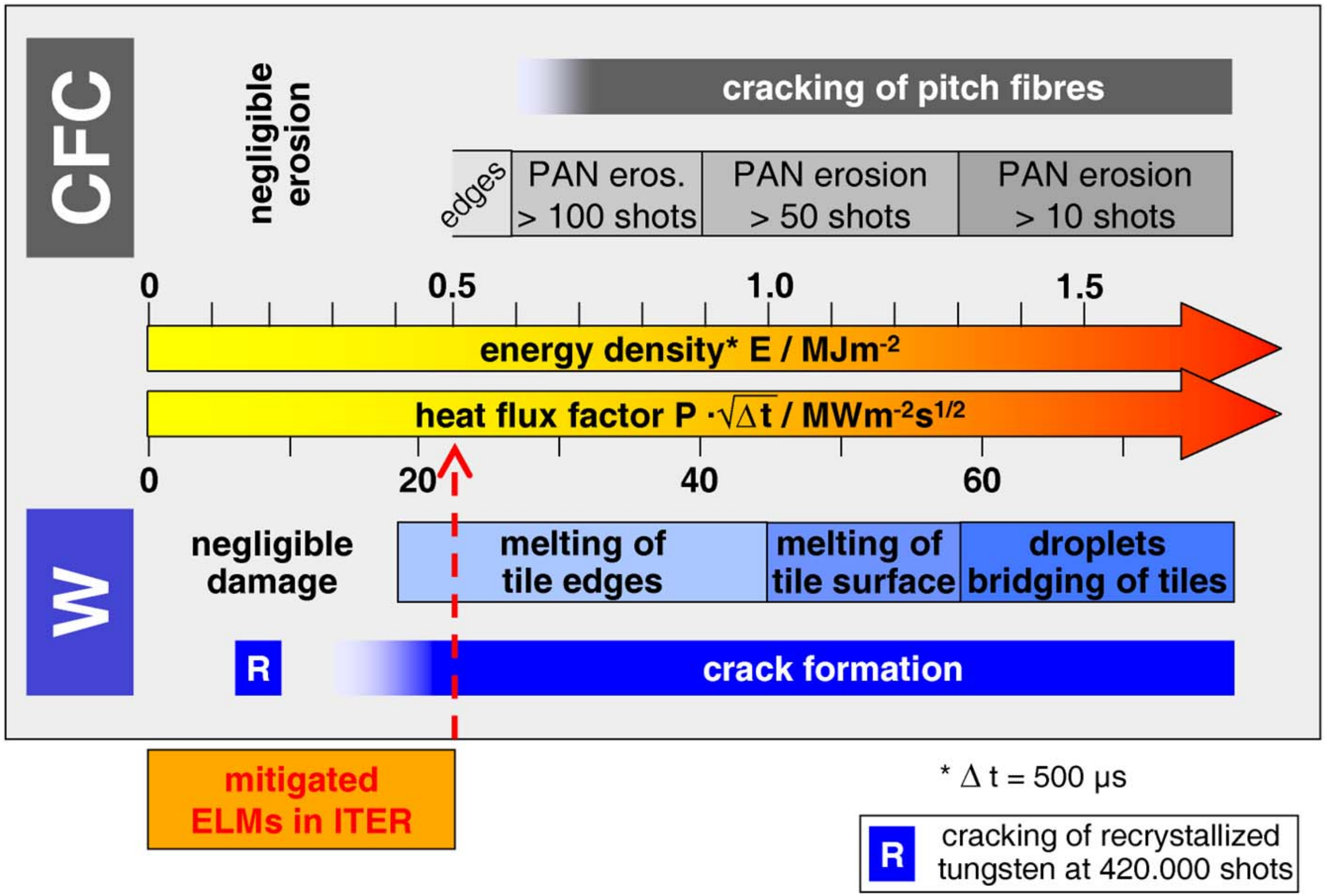
C-Mod

New Proposed Conductors and Conducting Structures have been Analyzed

- **Corsica and TokSys used to model vertical control.**
  - **Predict $(\Delta z/a)_{max}$ ~2% in ITER.**
- **Experimental data suggests:**
  - **Robust operation requires $(\Delta z/a)_{max}$ capability ~10% (C-mod, DIII-D and NSTX)**
  - **Calculated no-noise $(\Delta z/a)_{max}$ > experimentally achieved values on C-Mod.**
  - **ITER may require greater margin relative to no-noise calculated value.**
- **Passive structure (shorting the blanket shield modules) increases $(\Delta z/a)_{max}$ to 4-5% (~10% with upgrade to power supply voltage - VS1 = 9kV)**
  - **Major impact on the magnetic diagnostics, affecting control.**
  - **Design issue for blanket shield modules, remote handling and disruption loads.**
- **Use of in-vessel RMP coils predicts 50%.**

Humphreys, Gates, Portone

Material Issues are Very Serious



Unmitigated ELMS correspond to ~10MJ/m²

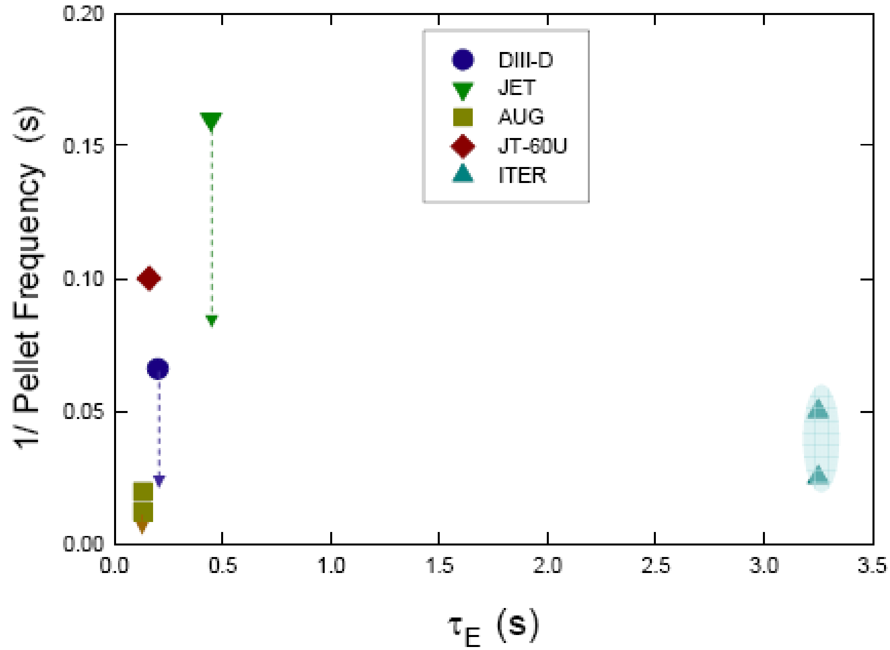
Scientific and Technology Mission of ITER can be put at Risk by Lack of ELM Control at Full Performance

- **Reduction of PFC lifetime, few full performance shots prior to divertor change out.**
  - **Experiments have shown significant damage to both CFC and W if 0.5 MJm^{-2} is exceeded, corresponding to 1MJ ELMs.**
  - **For 1000 high power shots, need to control ~10^7 ELMs from 20MJ to 1MJ corresponding to ~7% to 0.3% of the stored energy per ELM.**
  - **Occasional ELMs beyond the 0.5 MJm^{-2} are acceptable if limited to ~ 1.0-1.5 MJm^{-2} (CFC) and ~ 1.0 MJm^{-2} (W melting occurs).**
  - **Severe requirement on both reliability of mitigation technique and variability of ELM size.**
- **Increased plasma contamination and reduction of Q_{DT}**
- **Increased disruptivity**
  - **Slower progress + larger probability of PFC damage**
- ***World-wide effort is needed to develop improved ELM control techniques.***

Implications for Mitigation

- **Techniques that fully and reliably suppress ELMs are needed.**
  - **Operating modes such as QH or EDA are interesting but how they can be used on ITER has not been established.**
  - **Resonant Magnetic Perturbations (RMP), which stabilized ELMs on DIII-D, offer this potential.**
- **Controlling ELM size and variability such as by pellet pacing is an important backup strategy, if ELM suppression cannot be achieved.**
- ***Both RMP and pellet pacing require further experimental and theoretical work.***
  - **Both present significant technological challenges and sufficient ELM mitigation is not guaranteed for either.**
  - **Experiments are underway on C-Mod, DIII-D and NSTX to study this as well on AUG, JET and MAST.**

ITER Operates in a Different Parameter Region for Pellet Pacing

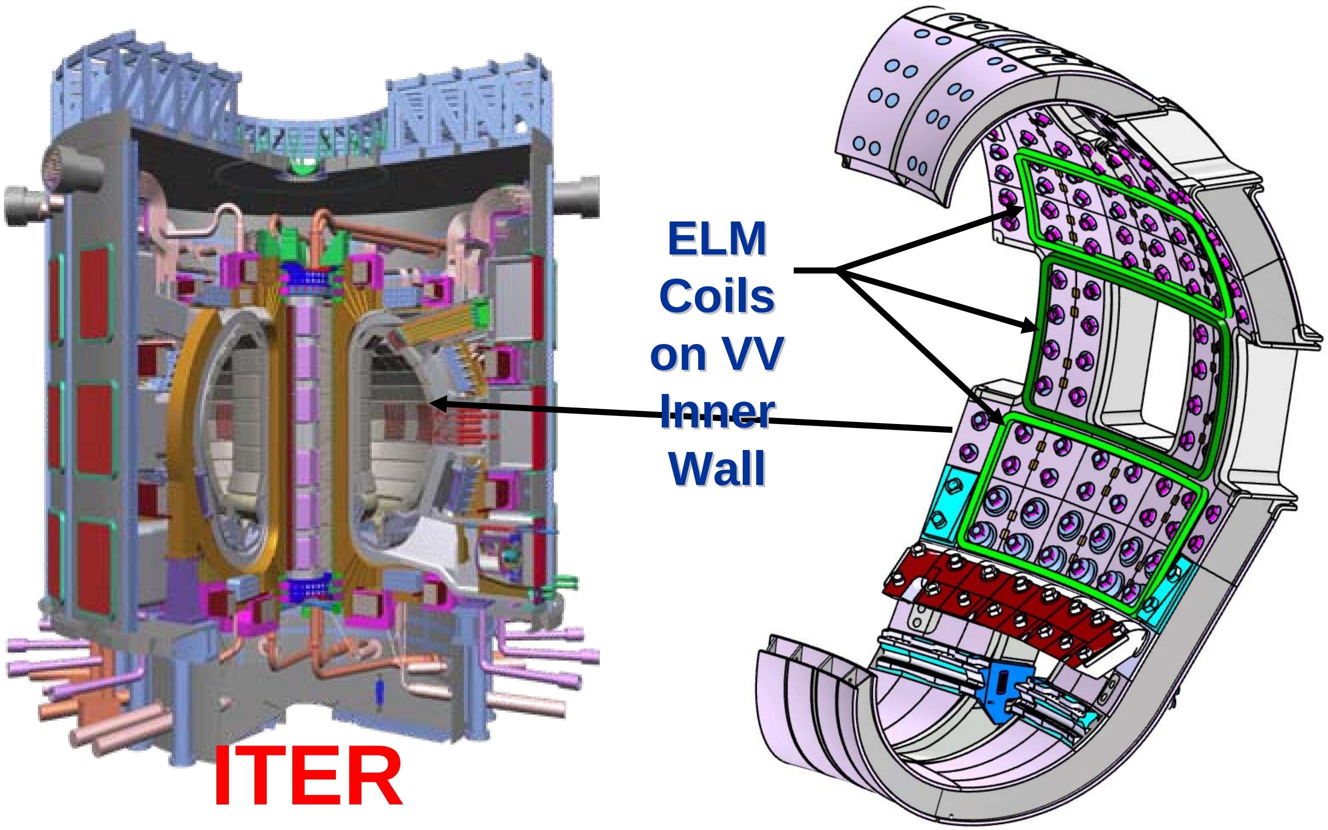


Future near term planned experiments are shown with dashed arrows

Baylor

- Pellet pacing experiments on AUG succeeded in reducing ELM size by 0.6.
  - Need to demonstrate reduction by .05 to .1
- In ITER need to inject ~100 pellets in τ_E.
- Future experiments on AUG, JET, & DIII-D will explore this regime.
  - What is the impact on energy confinement and pedestal height?
  - What is the impact of convective heat loss?
- Technologically more demanding, requires pellet development.

IO is Investigating Many Options for ELM Mitigation



ITER Tokamak

Vacuum Vessel Sector with Blanket Modules Removed

- **US community has been strongly engaged in both the physics analysis and conceptual design studies.**
  - IO has not selected a preferred option.

Recent Experimental Results on RMP Are Providing Critical Design Information But Issues Remain

- Island overlap criteria (Chirikov criteria greater than 1) is a necessary but not sufficient criteria.
  - Large equatorial midplane coils have not suppressed ELMs, though increased ELM frequency on JET and changed character on NSTX (type 5 to1), no effect on C-Mod.
  - Single row of off-midplane coils suppressed ELMs on DIII-D, with reduced operating range.
- DIII-D achieved $H_{98y,2}$=1 with RMP.
- Compatibility of RMP with pellet fueling under study
  - Several small transients (ELMs?) observed after a fueling pellet. Can they be reliably reduced? Further experiments planned
  - Effective particle confinement time reduced by RMP.
  - Small density decrease (7% in best case) after RMP application. Compensate with pellet fueling. Can we operate reliably near Greenwald limit and suppress ELMs?
- Very active area of research along with the related effects on plasma braking.

RMP Coils Have the Potential of Addressing RWM and Vertical Stabilization

- **VALEN results indicate, that depending on the design, RMP coils can be used to increase the operating range of β_N up to 3.8, exceeding the no-wall limit.**
  - **Port plug coils have greater potential (3.8) but impact diagnostics and heating systems.**
  - **In-vessel wall mounted options have engineering implications for the vessel and blanket shield modules.**
- **Preliminary analysis indicates that in-vessel coils can be used for vertical stabilization.**
  - **~200kAT required for full stabilization.**
  - **Engineering analysis required to see if that is feasible.**
- **Exploring an integrated solution to address ELMs, RWMs, and vertical stability.**

Bialek, Portone

STAC Issue Driven Work Plan Focused on Near-Term Issues Affecting ITER Design

- **Project is interested in getting best technical input.**
  - **Pushback on incorporating new systems is to be expected.**
  - **Raises the threshold for a compelling case.**

- **Changes to ITER requirements need international support and IO support.**
  - **Need to work closely with IO to improve the integrated design and not just address a specific issue.**
  - **Challenge to incorporate cutting edge results when an international consensus has not been achieved.**

- **USBPO has been effective in providing input to IO**
  - **Need an ongoing long-term mechanism to incorporate into the ITER design and research plans our best understanding and make timely assessments.**
  - **C-Mod, DIII-D, and NSTX are providing data from the current run addressing key issues.**